

PHASE-CONTRAST IMAGING WITH NEUTRONS

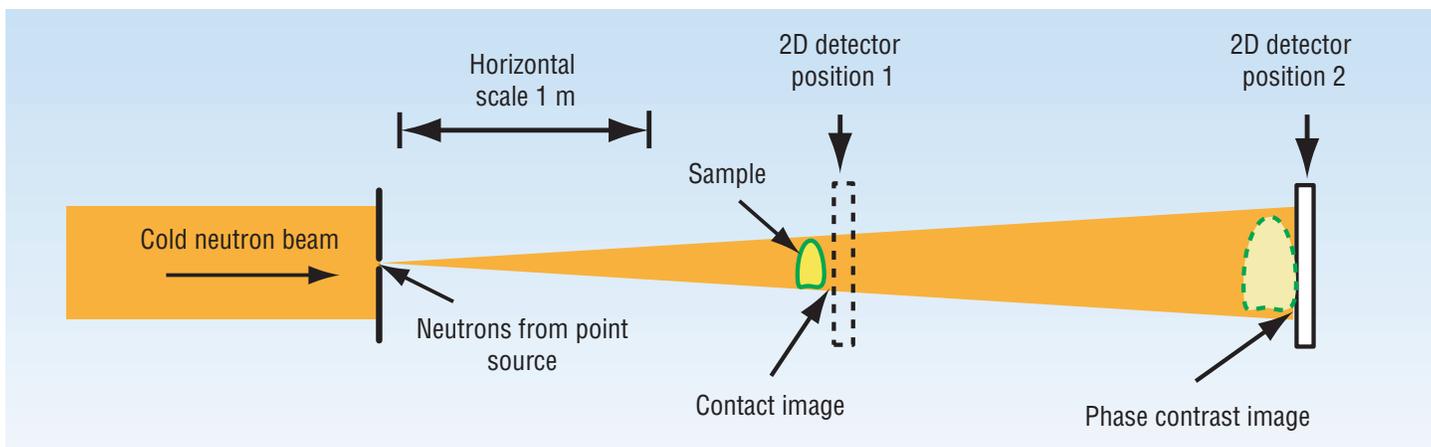


FIGURE 1. Experimental layout.

In-line phase-contrast images have been observed with many forms of radiation. Here we demonstrate that such images can be observed very simply with neutrons as well. Measurement of the phase of a neutron wave conventionally requires a delicate setup, carefully reducing interference-destroying vibrations of the parts through which the beam passes. Here we describe an alternative method that only requires measurements of intensity to extract phase information, and thus bypasses the need for the precise setup used in a conventional interferometric measurement.

A schematic of the setup used for the present experiment is shown in Fig. 1. To give them the required transverse coherence, monochromatic neutrons pass through a pinhole onto the sample. A 2-D CCD-type neutron camera then records the transmitted beam intensity through the sample at some distance from it (plane 2 in Fig. 1.) This downstream image is called the “phase-contrast image” because it is enhanced by Fresnel diffraction, since interference due to phase differences corresponding to edge effects has had a chance to develop. The radiographic image recorded immediately after the sample (plane 1 in Fig. 1) is called the “contact image,” and essentially contains a shadow of the object.

The contact and phase-contrast images of the bullet-shaped lead sinker, aligned with its axis perpendicular to the beam, taken with a 0.433 nm beam at the NCNR interferometer beam line NG-7 are shown in Figs. 2a and 2b. These are direct images, corrected only for the empty beam profile. In the normal radiograph (Fig. 2a) the extent and internal details of the sample structure are not clearly visible because of very low scattering and absorption. However, in Fig. 2b interference has enhanced the image intensity contrast at the

edges of the sample and at boundaries within the imperfections at the tip, rendering them clearly visible. Contact and phase contrast images of a wasp are shown in Figs. 2c and 2d, respectively. Notice that in the phase-contrast image all the delicate and thin organs of the wasp, e.g., antennae, leg segments, and wings, become visible. Since this method is so simple, many applications investigating internal features not otherwise visible are now possible.

Turning attention now to extracting phase information, after the beam has passed through the sample, particularly for an object offering little absorption or scattering, refractive variations within the sample still cause the beam’s phase to be modulated. As a result, the radiation *intensity* transverse to the direction of propagation is redistributed. By measuring these intensity changes alone one can retrieve the phase density profile of the sample without using an interferometer. The mathematical basis for this phase retrieval

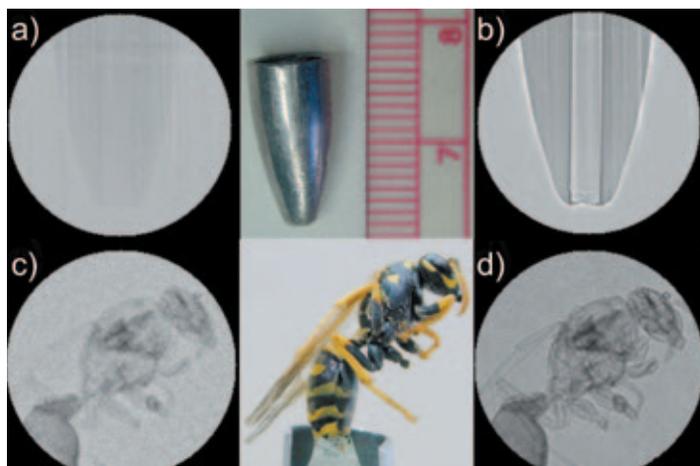


FIGURE 2. (a) contact and (b) phase contrast images of a lead sinker shown between them. (c) contact and (d) phase contrast images of a wasp.

technique is based on the quantum mechanical analogue of the so-called “Transport of Intensity Equation (TIE)” of a wave

$\sqrt{I(\vec{r}_\perp, z)}\exp(i\phi(\vec{r}_\perp, z))\exp(i2\pi z/\lambda)$, with irradiance, $I(\vec{r}_\perp, z)$ and phase $\phi(\vec{r}_\perp, z)$ transverse to the beam [1, 2]:

$$\frac{2\pi}{\lambda} \frac{\partial I(\vec{r}_\perp, 0)}{\partial z} = -\nabla_\perp \cdot [I(\vec{r}_\perp, 0)\nabla_\perp \phi(\vec{r}_\perp, 0)] \quad (1).$$

The TIE allows one to make a *quantitative* determination of the phase because the intensity of the propagated wave in a given transverse plane downstream is dependent on the intensity and phase upstream [3]. This technique is well developed for X-rays and electrons. Very beautiful experiments have been performed using both of these radiation types [4,5,6].

We recently carried out a series of experiments [7], for the first time with neutrons, to measure the phase modulated intensity changes caused by a sample and to quantify the observed phase profile using this technique. The experiments were performed at NG-7 and also at NG-0. NG-0 is a curved neutron guide providing a polychromatic neutron beam with the Maxwellian peak centered around 0.432 nm. At the NG-7 guide a PG(002) crystal was used to extract a beam in the range of 0.235 nm to 0.475 nm.

Both contact and phase-contrast images were recorded in order to obtain the derivative on the left side of Equation (1). The phase-contrast image was taken with the CCD placed 1.5 m to 1.8 m from the sample. The images from the CCD are downloaded to a computer and the centroids of the neutron events are deter-

mined by hardware processing, achieving a best-case resolution of about 60 μm .

Figure 3a shows an image constructed from such an analysis of the lead sinker (of Fig. 2) whose longitudinal axis is nearly aligned with the incident beam. In Fig. 3b is plotted a profile of the retrieved phase along AB (blue curve). This profile was obtained through Fourier processing of the data. The predicted phase profile (dotted curve) determined from the sample geometry and orientation is in excellent quantitative agreement with the experimental data.

This phase retrieval technique works with a polychromatic beam and is not constrained by low flux. We plan to extend both of these types of measurements using polarized and very cold neutrons to study magnetic domain structures, interface boundaries and density variations in multi-layer thin films. We also plan to carry out tomographic measurements in the near future.

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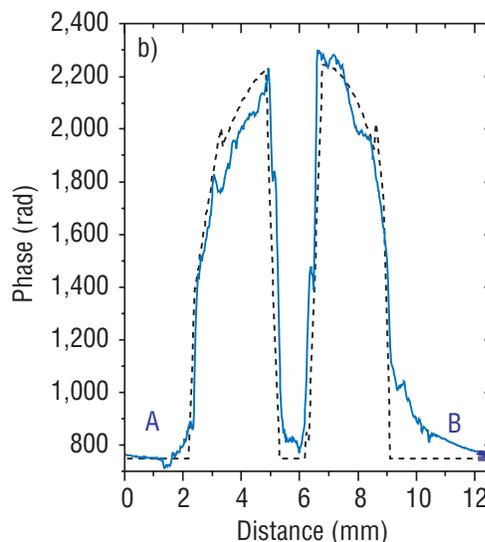
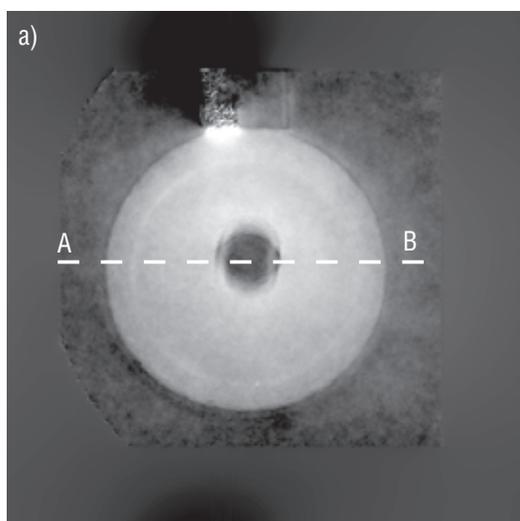


FIGURE 3. a) reconstructed image of lead sinker along beam direction; **b)** measured (blue) and computed (dotted) phase variations along line AB in a).